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Water savings in irrigated agriculture

A framework for assessing technology and management options to reduce water losses

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Abstract: *Water saving in agriculture often refers to reducing the amount of water abstracted or diverted and used for different purposes. However, this is not the only option: reductions in water use can also be achieved by using appropriate techniques for irrigation, applying relevant management practices, using water from alternative sources or influencing behaviour – for example, via awareness-raising, dissemination of best practices, regulation, water pricing and/or the use of financial incentives. While these options or responses will help to reduce pressure on water resources, if implemented in isolation they limit the extent to which water is actually 'saved'. More often, they need to be considered as part of a broader integrated approach to water management. This paper presents a framework for identifying areas in which scope for achieving water savings exists and then reviews the possible means of action and the constraints to implementation. The framework is intended to inform polices aimed at improving the sustainability and allocation of water to irrigated agriculture.*

Keywords: *abstraction; consumptive use; efficiency; soil; water resources*

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Agricultural irrigation constitutes the largest user of freshwater, accounting for around 70% of global abstraction (Fischer *et al*, 2007). However, increasing demands for food, feed, fibre and biofuels driven by population and economic growth, coupled with growing competition for water resources, have highlighted the limitations on water supplies for agriculture. Increasing water efficiency and saving water in agriculture have become major industry and societal priorities, not only in arid and semi-arid environments (EEA, 2012), but also in temperate and humid regions (Knox *et al*, 2010). Indeed, in many countries, increasingly limited access to affordable, reliable supplies of water for irrigation has become a major constraint to agricultural development, with climate change threatening to exacerbate the problem due to increased water demands and reduced supplies (Falloon and Betts, 2010). Improving water productivity, or more 'crop per drop', coupled with identifying opportunities to save water and improve efficiency in irrigated agriculture, has become the focus of government agencies, regulators, decision makers and the research community (Lankford, 2011).

Water-saving practices in irrigated agriculture may be broadly categorized into engineering, agronomic, management and/or institutional measures. The success of each of these depends largely on the level of their integration and underlying socioeconomic conditions (Kulkarni, 2011). One of the main focus areas has been at a system level where innovative technology and management approaches could be adopted, including new approaches to abstraction control, transport, storage, delivery and consumption of water. At each step in this chain of water use, scope for reducing losses and measures to limit the 'non-beneficial' losses can be

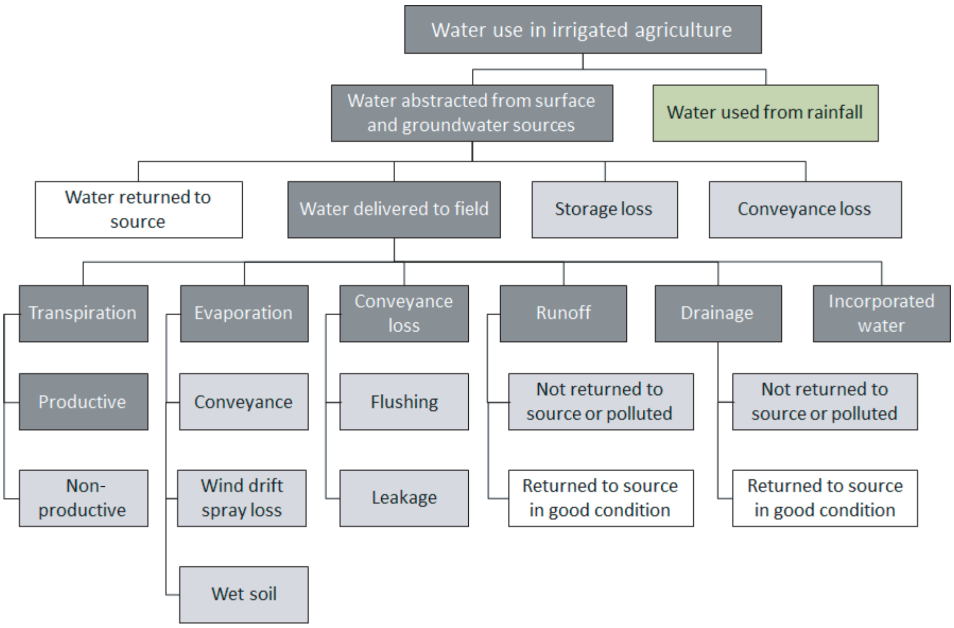

Figure 1. Framework for identifying options to save water in irrigated agriculture.

identified. The range of options or responses to deliver water savings is the focus of this paper. For each measure, there are alternative means of action, each with their own barriers and enablers.

In trying to identify opportunities for water saving, it is useful first to map the main areas of water use and their interdependencies. Figure 1 presents a suggested framework. The total amount of water used in crop production can be derived from rainfall or water abstracted from surface and/or groundwater sources. In arid environments, the emphasis is on abstracted water for irrigation; conversely, in humid regions, irrigation is less important and supplemental to rainfall. In general, where water resources are constrained, most emphasis on water saving is usually placed on abstracted water (often referred to as 'blue' water) as this has a much higher opportunity cost, although reducing rainwater (or 'green' water) use may also have environmental and water resource benefits.

In Figure 1, the light grey shaded boxes represent 'non-productive' water losses (for example, storage loss, wind drift, leakage). Technological and management approaches to minimize these will result in water savings. The white boxes refer to abstracted water that is not 'consumed' but returned to the environment in a useable condition and available as a resource. In the long term, there is no (or limited) benefit in reducing these losses; however, there may be gains in the short term through reducing the volume of water used during peak periods. For each 'non-productive' water loss identified in Figure 1, the means of action to save water and constraints to implementation are briefly summarized below.

Storage losses

The loss of stored water from reservoirs through evaporation is inevitable, but can be significant in arid and semi-arid climates. Water evaporates much faster from open water surfaces than from the surrounding landscape due to lower surface resistance. Water from smaller water bodies evaporates at a faster rate than from large bodies under similar climate conditions due to turbulence and edge effects. Therefore, the evaporative loss per unit area is greater from farm dams compared with, say, large storage reservoirs for public water supply. It is important to note that the impact of farm dams on storage losses will be greatest during periods of high evaporation, which often coincide with drought periods and times when irrigation demand peaks. Evaporation rates are affected by the latitude of the water body (solar energy input), air and water temperature, air pressure, wind velocity over the water surface and water turbulence. In years with little precipitation, evaporation losses may exceed gains from rainfall. Leaks in reservoirs can also result in water being lost.

The use of covers and shades, monolayers or windbreaks has potential to reduce reservoir evaporation. Floating covers can reduce evaporation losses and assist in temperature stabilization, and are most suited to small dams. They can also eliminate algal growth and contamination from airborne pollutants. They can be designed to allow for fluctuating water levels, rainwater drainage and routine access. Floating covers are usually manufactured from reinforced polypropylene, and rates of reduced evaporation close to 85% with suspended shade cloth covers have been reported in south-east Spain. In addition to floating covers, floating objects can be used, as their installation is easier and cheaper. Some biological covers, such as lily pads and duckweed, have potential to reduce evaporation from the surfaces that they colonize. Silicone-based monolayers are also used, but their uptake has been limited.

Windbreaks can reduce the speed and turbulence of air movement over the water surface and reduce evaporation rates by 20 to 30%, depending on the density, height, orientation and distance from the water. Both natural (trees) and artificial windbreaks are used. Natural windbreaks provide other benefits in terms of shade and habitat. Storage reservoirs can also be constructed or modified to reduce their evaporation rates proportionally – by designing them either with deeper storage and smaller surface areas, or as a cellular construction that divides the storage into smaller units to reduce wind action and allow water depth to be maximized by shifting water between cells.

Constraints include the short lifespan of monolayers and the fact that displacement by wind means they have to be reapplied quite frequently (typically every one to two days). Furthermore, chemical monolayers are not as effective as physical methods. The evaporation reduction efficiency of biological layers is much lower than other methods available and has received little attention. Natural windbreaks compete for water and, in some situations, need to be irrigated during establishment.

Conveyance losses

Conveyance or distribution efficiency is generally a major concern for irrigation districts that supply a group of individual farmers. Indeed, there are significant differences in conveyance efficiency depending on the type of irrigation network. For example, in Greece, the average conveyance efficiency was estimated to be 70% for earth-lined channels, 85% for concrete-lined channels and 95% for piped systems (Karamanos *et al*, 2005). At a European level, potential water savings could amount to circa 25% of the total water used for agricultural irrigation, so the scope for savings is significant (WssTP, 2010).

Canals that carry between 30 and 150 l/s can lose between 10 and 15% of flow via seepage and water transpiration from in-channel weeds. Lining a canal will not eliminate these losses completely, but roughly 60 to 80% of water lost in unlined canals can be saved by surface lining (FAO, 1992). Replacing open canals with low-pressure piped systems can reduce evaporation losses, the land-take for conveyance and delivery time for water to reach the target fields, and can increase the equity of water distribution between end-users. In France, irrigation scheme modernization involving the conversion of gravity irrigation networks to pressurized systems helped save around 300 million m^3 per year (BIO Intelligence, 2012). Automation involving replacement of manual flow-control structures and flowmeters on-farm, with automatic control gates to regulate and measure channel flow, can provide data to manage and monitor water use better and in real time and reduce unnecessary water wastage.

Transpiration

Non-productive

There are opportunities to reduce non-productive transpiration: that is, transpiration of unwanted vegetation (such as weeds). If weeds develop deep roots, they can extract and transpire more water than would be lost by soil evaporation alone. Soil tillage reduces weed coverage and reduces unproductive transpiration; however, it can also bring wet soil to the surface and increase soil evaporation. Chemical weed control can help minimize the competition for water from weeds and therefore reduce soil water depletion. Herbicide-resistant (GM) crops can be used. Although the removal of non-productive vegetation will reduce total transpiration, this may not result in water saving if it is replaced by evaporation from bare soil. Despite these possible measures, the practical feasibility of actually reducing non-productive transpiration is limited. The use of herbicides can also reduce biodiversity in fields and lead to increased soil and water pollution.

Reducing productive transpiration

For most crops there is a linear relationship between plant growth and transpiration (under constant temperature and relative humidity); therefore transpiration cannot be reduced without reducing plant growth. However, genotypes may differ in their transpiration efficiency (dry matter per unit of transpiration) and there is scope for plant improvement to select more efficient plants. In recent years, selective breeding has increased the water use efficiency (WUE) of some crops and partitioning of dry matter to the harvestable parts of the plant. Two approaches to limiting water uptake by plants, without reducing yield or quality, are deficit irrigation (DI) and partial root-zone drying (PRD).

DI involves giving plants slightly less water than potential evapotranspiration so that a moderate soil water deficit develops during the season. This has been shown to increase WUE, particularly in crops typically resistant to water stress, such as grapes (Costa *et al*, 2007). It has also been shown to be effective in some temperate field crops (for example, potatoes), but requires very careful management, with too much water stress at the wrong growth stage resulting in significant yield and quality losses. PRD involves alternately wetting and drying two spatially distinct parts of the plant rooting system. It has shown potential to increase irrigation water use efficiency without reducing yields. For example, Shahnazari *et al* (2007) found that when potatoes were irrigated with a PRD regime, 30% of irrigation water was saved while maintaining tuber yield, leading to a 61% increase in irrigation water use efficiency. They concluded that PRD was a promising water-saving strategy for potato production in areas with limited water resources. The main constraints are that DI and PRD are much easier to manage in arid conditions or under protected cropping (greenhouses or polytunnels), as unpredictable rainfall can interrupt drying cycles. Both techniques also rely on precise irrigation timing, frequency and application, and are thus more suited to drip (trickle) irrigated crops than overhead (sprinkler) or surface-irrigated crops.

Evaporation

Conveyance losses

Similar to the larger irrigation network distribution systems, efforts can also be made to target higher efficiency in on-farm conveyance by preventing evaporation losses through replacing open canals with low-pressure piped systems, but conversion is costly. However, a major increase in energy costs associated with operating pressurized systems in Spain has forced farmers to reconsider the economics of investment, driven by the need to save energy rather than water (Rodríguez-Díaz, 2012).

Wind drift and spray losses

Above-canopy spray evaporation loss represents the portion of water lost to the atmosphere during the time it takes to travel from the sprinkler nozzle to the crop canopy. Wind drift and spray losses occur as wind carries droplets away from the irrigated area. Droplets may evaporate on their direction of trajectory or fall outside the irrigated area. Another portion of water is intercepted by the crop canopy, with part of this lost to evaporation. Evaporation losses are affected by equipment (such as nozzle size, angle, operating pressure and height of sprinkler) and climate (such as air temperature, air friction, relative humidity, solar radiation and wind speed), with droplet size reported to be the most important factor (Uddin *et al*, 2010). Lorenzini (2004) reported 3.7 to 8.6% droplet evaporation for droplet diameters ranging from 0.3 to 3.0 mm. Wind drift can also negatively impact on uniformity of water application, with over-application leading to deep drainage.

Switching technology from surface and sprinkler irrigation to drip irrigation offers potential for water saving. In the UK, the Environment Agency (EA, 2009) reported typical efficiencies of 75% for sprinklers and 90% for drip (trickle) systems. Water savings are therefore possible when switching to drip, but only if accompanied by higher levels of in-field management. Without advice and support, switching technology will not lead to water savings. For example, García (2002) and OECD (2006) showed that drip irrigation had led to an increase in cropped areas (that is, no water saved) in Spain, or had not been used to its full potential in Crete because of insufficient technology support. Weather conditions during irrigation can also impact on potential water savings. Playan *et al* (2005) showed that the best conditions for limiting wind drift and spray losses (under 5%) were when wind speeds were below 2 m/s, relative humidity was above 80% and air temperature was below 20°C.

Wet soil

Evaporation and transpiration may occur simultaneously and are difficult to differentiate. Apart from the water availability in the upper soil layer, the evaporation from a cropped soil is mainly determined by the fraction of solar radiation reaching the soil surface. This fraction decreases over the growing period as the crop canopy develops and shades the ground area. When the plant is small, water is predominantly lost by soil evaporation, but once the plant is well developed and covers the soil, transpiration becomes the dominant process. If water could be conserved in the soil for use later, then irrigation water requirements could be reduced (particularly for widely spaced row crops).

Frequent rain, irrigation and water transported upwards in soil from a shallow water table (via capillarity) can wet the soil surface. However, where the interval between rain and irrigation is long and the ability of the soil to conduct moisture to the surface is small, the water content in the topsoil drops, the soil surface dries and soil evaporation decreases rapidly. Studies have shown that considerable reductions in soil evaporation can be achieved, increasing water availability later in the season (Todd *et al*, 1991; Yunusa *et al*, 1994).

Mulching can be used to prevent water loss by covering the soil with permeable materials such as sand, gravel, perforated plastic or organic waste (such as straw), thereby creating a barrier to evaporation of soil water. Mulching not only retains moisture by slowing the evaporation process, but also contributes to reducing rainwater run-off; builds soil and improves soil health; improves nutrient absorption; kills grasses and weeds without the need for herbicides; encourages beneficial organisms within the soil; and helps to reduce soil erosion. Todd *et al* (1991) showed that straw mulch reduced the mean daily soil evaporation from bare unshaded soil by about 0.5 mm/day under dryland conditions, over 1 mm/day under limited irrigation and over 2 mm/day under full irrigation.

With localized irrigation, water is applied at low pressure close to each plant. This can improve water efficiency as most of the applied water is taken up by the plants rather than lost to evaporation or drainage. This method is suitable for high-value crops such as fruit and vegetables. Subsurface drip irrigation is also a low-pressure system that uses buried drip pipes, and can help improve yield by eliminating surface water evaporation. This method is particularly suited to arid, semi-arid and windy areas with limited water supply. As water is applied directly into the root zone and not on to the soil surface, the germination of annual weeds is also reduced. Some crops have been shown to benefit from the additional heat provided by dry surface conditions, producing more crop biomass, provided that water is sufficient in the root zone. However, high capital and maintenance costs associated with localized irrigation generally make it unsuitable for many field-scale crops. Soil type can also limit suitability, since low application rates mean drip irrigation uniformity is dependent on good soil capillarity.

Tillage can influence the scope for water conservation, with no-till systems shown to lose less water through evaporation than conventional tillage. Lipiec *et al* (2006) showed the effect of tillage on soil hydrology and found that conventional tillage enhanced infiltration and water storage capacity. Since tillage also involves modifying the physical soil characteristics, it can influence plant root development by modifying patterns of soil water uptake.

Conveyance

Flushing and leakage control

On-farm conveyance efficiencies and water savings can also be enhanced by regular flushing of drip irrigation systems and reducing system leakage. Regular maintenance including back-flushing filters and mainlines helps to ensure that irrigation system performance (uniformity) is not reduced by sediment build-up and clogging. Potential water savings in micro-irrigation can quickly be eliminated by poor filtration and system management.

Run-off

Not returned to source or polluted

Run-off during irrigation can occur when the application rate exceeds the soil infiltration rate, or when irrigation occurs on soil that is already wet and cannot receive the amount of water being applied. Matching irrigation application rates to soil infiltration characteristics is fundamental to system design, and irrigation water run-off should not be significant in well designed and managed systems. However, run-off of irrigation water can occur where, for example, (i) mobile irrigation equipment (such as a rain gun) is used across fields with a range of soil types and slopes, (ii) local patches of soil with low infiltration capacity occur, (iii) soil management has resulted in localized compaction (as in wheelings) or (iv) at the end of centre pivots where instantaneous application rates are very high. Run-off can also occur when the irrigation application depths exceed the water-holding capacity of the soil. This is rare under overhead irrigation, but more typical in surface (furrow) irrigation in order to ensure adequate 'contact time' at the bottom end of the furrow.

Reducing surface run-off not only saves irrigation water, but also reduces soil erosion, phosphate and other chemical losses and increases the effectiveness of rainfall (reducing the need for supplementary irrigation). Although run-off water may find its way into drainage channels and eventually into watercourses or groundwater, it may be returned at a time, place or quality that makes it less useful, and can therefore be considered as a consumptive use. Changes in application technology, improved management, and modifications to soil structure and better in-field management (scheduling) can all help reduce run-off risks and thereby help save water.

Switching irrigation technology to use overhead systems with smaller droplet sizes, such as micro-sprinklers, can help reduce run-off and the risk of capping, particularly on fine-textured soils (which can lead to run-off from both irrigation and rainfall), whilst systems with a very low application rate may be useful on problematic soils. Subsurface drip irrigation effectively eliminates surface run-off as water is applied within the root zone. Better control of irrigation equipment – for example, through the use of smart technologies and precision irrigation to improve uniformity (Monaghan *et al*, 2013) or adjust application rates in real time in relation to soil conditions and crop development – can also reduce run-off.

Practices that encourage local water retention on the soil surface can also help reduce surface run-off rates. For example, blocking furrows ('furrow diking' in the USA) has been advocated in semi-arid agriculture for many years (for example, Dagg and Macartney, 1968), but more recently the technique has been tried with supplementary irrigation in temperate environments. For example, Nuti *et al* (2009) evaluated the use of furrow diking for supplementary irrigated cotton in Georgia (USA). It was shown to reduce irrigation requirements, improve yield and net returns when rainfall was periodic and drought was not severe. In field-scale agriculture, creating small depressions (up to 200,000/ha) in raised beds is also used to reduce run-off and aid percolation into the soil. Patrick *et al* (2007) estimated that surface run-off could be reduced by 95% on some soils using this approach.

Maintaining good soil structural condition is also important to maintain soil infiltration capacities. Avoiding heavy trafficking and compaction is central to good agricultural practice. Similarly, agronomic practices that encourage rapid and complete ground cover reduce the exposure of bare soils and risk of capping on silty soils and hence reduce the risks of run-off. Accurate knowledge of soil water status prior to irrigation means that application can be scheduled to reduce the risk of run-off occurring from over-irrigation. On light soils, surface run-off from irrigation due to saturated overland flow is unlikely, as light soils can absorb water even when they are wetter than field capacity (although this may be subsequently lost due to drainage). In furrow irrigation, although some run-off is inevitable, practices such as 'surge irrigation' or 'furrow blocking', when applied correctly, can also minimize run-off losses.

Despite a range of potential options, reducing run-off does not automatically result in water savings, as drainage may be substituted for surface run-off if irrigation scheduling is poor or rainfall is excessive. Switching from overhead to micro (drip) irrigation potentially offers water savings, but only on appropriate soils and for selected crops. The use of tied ridging to eliminate run-off on sloping fields can introduce other problems, including the need for additional field operations using mechanical equipment to remove them prior to harvest. For example, many farmers are reluctant to use tied ridging because it disrupts the smooth passage of heavy harvesting machinery lifting delicate crops.

Drainage

Not returned to source or polluted

On light soils or in well drained conditions with gentle slopes, drainage of water downwards from the root zone may be much more significant than surface run-off. As it is not visible, it does not raise immediate concerns and can continue unnoticed. Drainage of water out of the root zone will occur when the root-zone soil water content is raised above field capacity. If drainage is unimpeded, this water is effectively lost, and with it, nutrients dissolved in the soil water. If drainage is impeded, it can lead to localized waterlogging. These situations can be avoided by controlling the drainage, or by capturing and recycling the drainage water.

Poor uniformity of water application can result in drainage losses even where part of the crop is not fully irrigated. Furrow irrigation, for example, will necessarily apply more water at the top end of the field than at the bottom, as the bottom end will always have a shorter 'contact time', although practices such as 'surge irrigation' can increase uniformity. For example, Horst *et al* (2007) showed that surge flow on alternate furrows reduced irrigation water use by 44% and led to an application efficiency of almost 85%. Many overhead irrigation systems (such as rain guns) are often non-uniform, and farmers compensate by over-irrigating to ensure that the driest parts of the field receive sufficient water, leading to drainage losses in the wetter parts. A prerequisite for reducing drainage losses is a uniform irrigation, which may be achieved with more precise application systems such as booms, centre pivots or drip irrigation.

Good scheduling of irrigation timing and amounts will aim to maintain soil water conditions drier than field capacity in order to minimize drainage losses arising from irrigation. However, keeping the soil close to field capacity increases the risk of drainage losses from unpredictable rainfall. Good irrigation practice in environments where rainfall is unpredictable means not returning the soil to field capacity with irrigation, but maintaining some storage capacity (buffer) for rainfall. This maximizes the effectiveness of rainfall and reduces the need for subsequent irrigations.

Finally, soil texture is the major determinant of the water-holding capacity of a soil. Larger pores in sandy soils allow water to infiltrate and drain more quickly, leaving smaller amounts stored within the soil profile. Loams, silt loams and clay loams have a broader range of pore sizes, many of which store water for longer periods. Conditioners (amendments) can be applied to the soil to increase the water retention capacity of the soil. Organic residues, peat and hydrophilic polymers can be used to improve water retention in sandy soils; however, in most cases there is no practical way to change the soil texture and other practices should be used to try to increase the water-holding capacity of sandy soils. The high cost of soil conditioners to improve water retention means that this technique is usually only really viable on small areas, such as for sports turf (for example, golf courses).

Alternative approaches to water saving

The alternative to identifying technological and management options to save water is to switch to other sources of water, thereby reducing pressure on ‘conventional’ water sources (surface and groundwater) or to reduce pressure on conventional sources at critical times of the year. This approach involves water being either reused, stored on-farm (collecting water during periods of high flow) or harvesting rainwater. Using these approaches, no water is physically ‘saved’, but the impact on water bodies and/or the impact during the season when water resources may be constrained is much lower.

Finally, water-saving approaches in agriculture can be driven from a socioeconomic context, with strategies to change practices by raising awareness and providing incentives to use less water through, for example, training and extension, communication, regulation, water pricing and trading, and benchmarking. These measures provide an indirect approach to water saving, by allowing the farming sector to drive improvements in performance within the industry and providing sufficient flexibility to select the most appropriate approach for a particular farming system.

Way forward

Irrigated agriculture is facing rising competition for access to reliable, low-cost, high-quality water. Globally, it constitutes the largest use of freshwater, with irrigation representing nearly three-quarters of total water use. But of this, only half is estimated to reach the intended crop – the rest being ‘lost’ somewhere between the point of abstraction and the crop. In many developing countries the proportion used is even higher (Turral *et al*, 2010), highlighting the dependence of rural-based economies on water for agriculture (Knox *et al*, 2012). Clearly, improving water efficiency and promoting the uptake of innovative technological and management strategies to support water saving have become a major priority. But securing water for agriculture and making better use of limited supplies in future will also be essential to meet the changing food demands of a burgeoning global population. Many of the potential adaptation options highlighted here to save water or use less are ‘no regret’ – in that they already make sense by helping to solve existing water resource issues and constraints, which themselves will contribute to increasing the agricultural sector’s adaptability to both future water scarcity and climate change.

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